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(2012)

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Goscinski, Wojtek James (Ed.)

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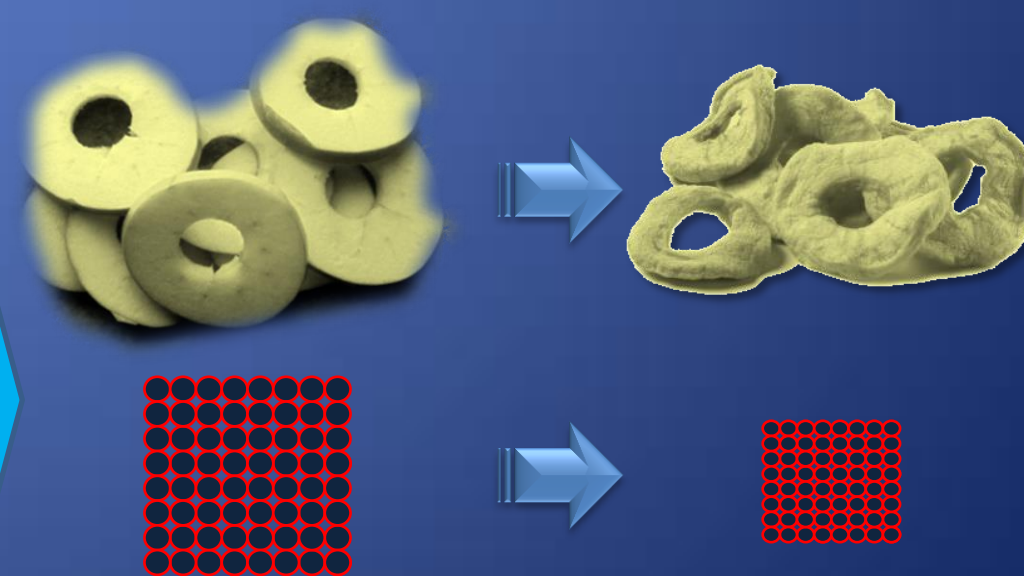
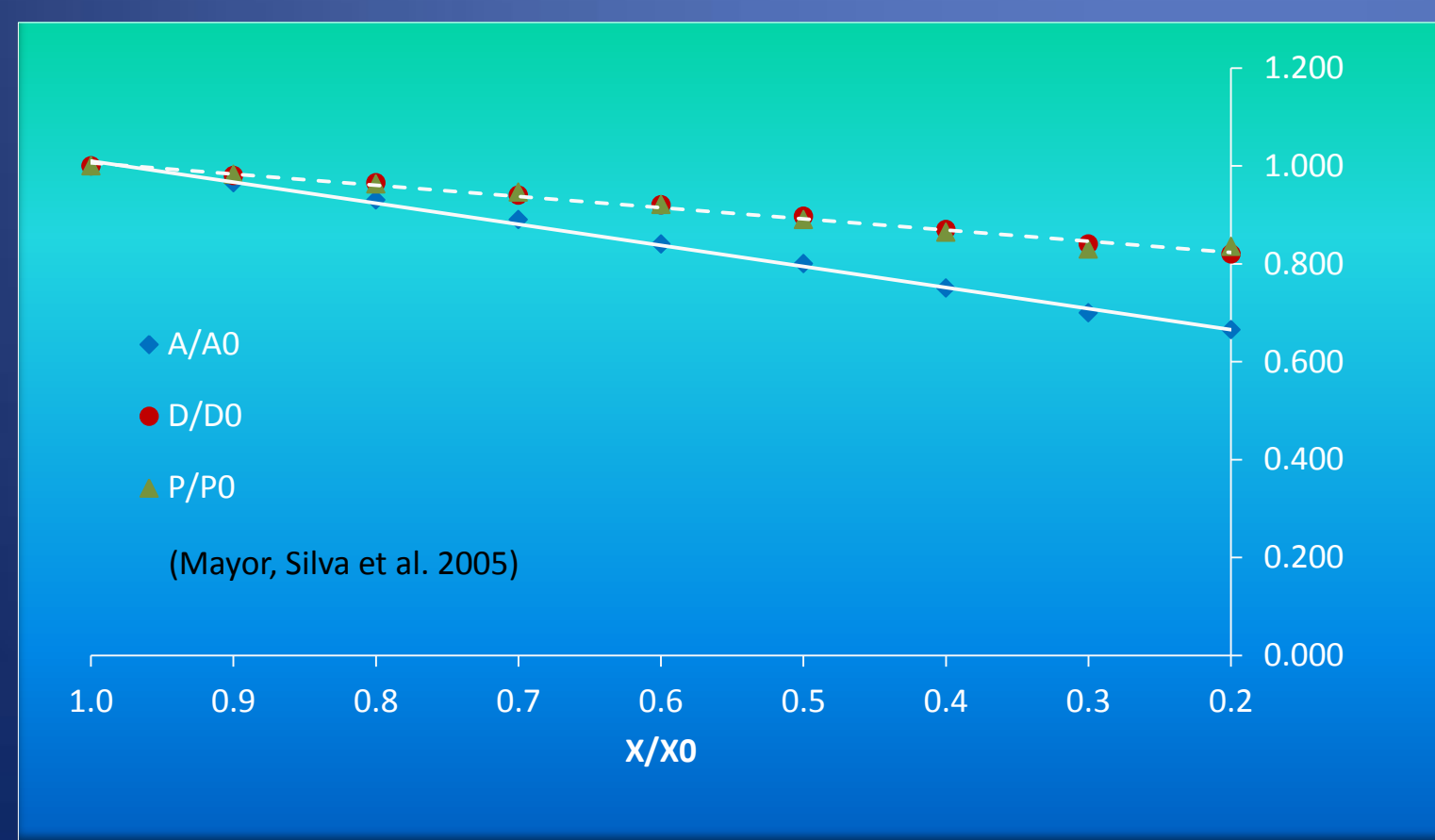
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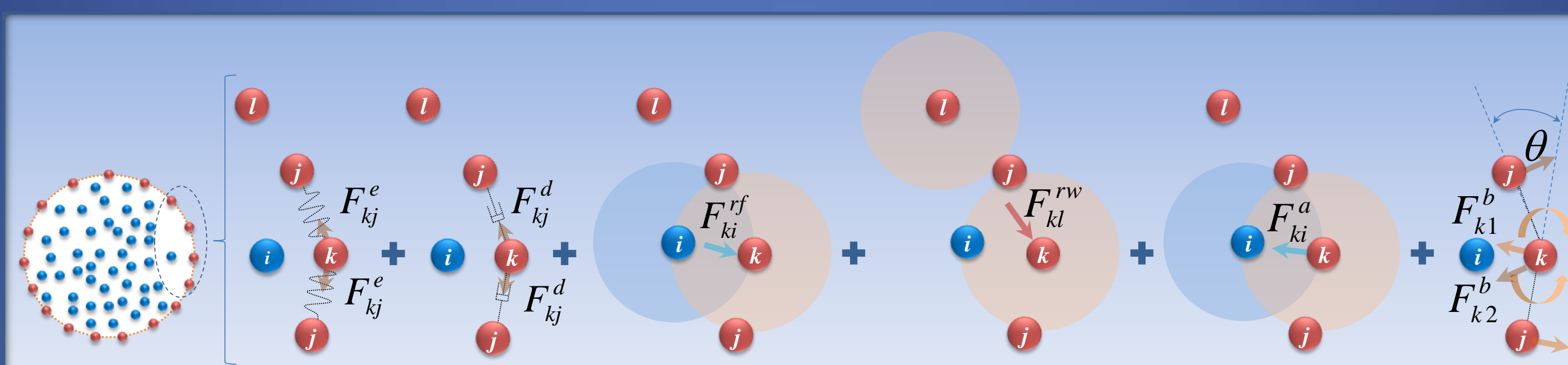
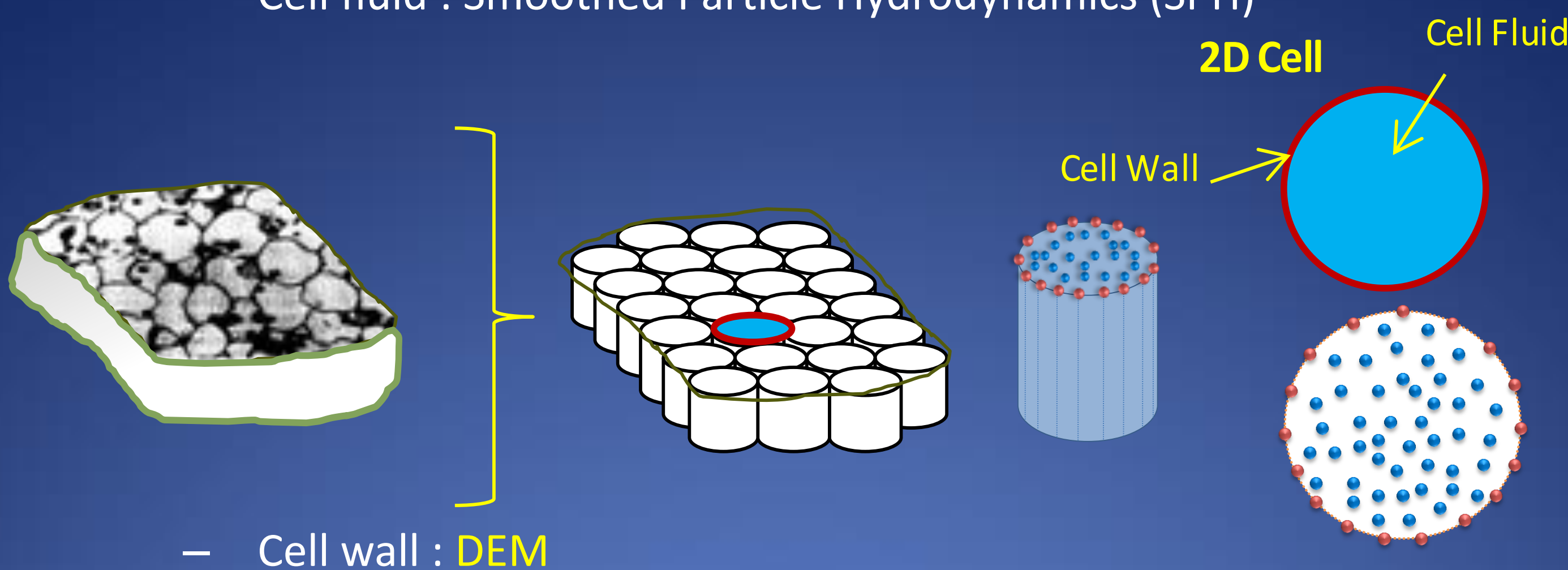
Background

- Food drying is a significant industry
- Numerical modeling and simulations are essential for product/process improvements
- Problem domain:
 - Excessive deformations
 - Multi-phase
 - Discrete
 - Multi-scale
 - Phase change
- No reliable software available for micro-structural modeling
- Experimental Findings: Direct relationship exists between moisture content and cellular deformations



Methodology

- 2-D Single cell model
 - Cell wall : Discrete Element Method (DEM)
 - Cell fluid : Smoothed Particle Hydrodynamics (SPH)

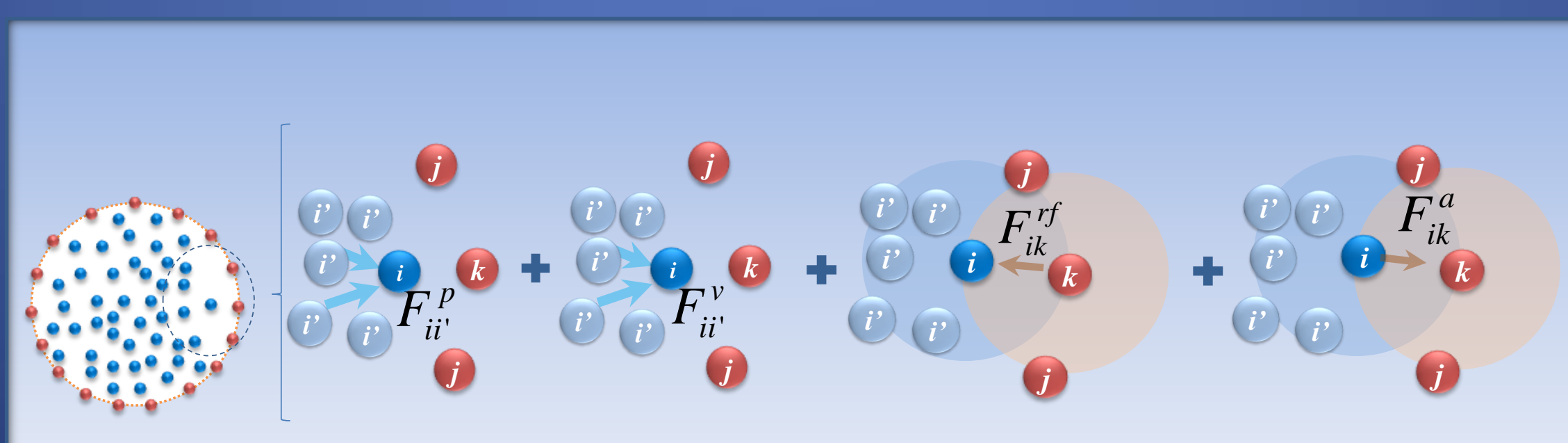


$$F_k = F_{kj}^e + F_{kj}^d + F_{ki}^{rf} + F_{kl}^{rw} + F_{ki}^a + F_k^b$$

$$F_{kj}^e = Gz_0 t_0 \left(\lambda_\theta - \frac{1}{\alpha^2 \lambda_\theta^5} \right) \quad F_{kj}^d = -\gamma v_{kj} \quad F_{ki}^{rf} = \begin{cases} f_0^{rf} \left[\left(\frac{r_0}{r_{ki}} \right)^8 - \left(\frac{r_0}{r_{ki}} \right)^4 \right] \left(\frac{1}{r_{ki}^2} \right) & \left(\frac{r_0}{r_{ki}} \right) \geq 1 \\ 0 & \left(\frac{r_0}{r_{ki}} \right) < 1 \end{cases}$$

$$\alpha = \sqrt{\frac{\beta + \sqrt{\beta^2 - 4(\beta - 1)/\lambda_\theta^6}}{2}} \quad F_{ki}^{rf} = f_{ki}^{rf} x_{ki} \quad F_k^b = \frac{k_b}{l} \tan(\Delta\theta/2)$$

- Cell fluid : SPH



$$F_i = F_{ii}^p + F_{ii}^v + F_{ik}^rf + F_{ik}^a$$

$$F_{ii}^p = -m_i \sum_{i'} m_{i'} \left(\frac{P_i}{\rho_i^2} + \frac{P_{i'}}{\rho_{i'}^2} \right) \left(\frac{1}{z} \right) \nabla_i W_{ii'}$$

$$F_{ii}^v = m_i \sum_{i'} \frac{m_{i'} (\mu_i + \mu_{i'}) v_{ii'}}{\rho_i \rho_{i'}} \left(\frac{1}{z} \right) \left(\frac{1}{r_{ii'}} \frac{\partial W_{ii'}}{\partial r_{ii'}} \right)$$

$$\frac{d\rho_i}{dt} = m_i \sum_{i'} v_{ii'} \cdot \nabla_i W_{ii'}$$

$$\frac{dz}{dt} = \frac{z(t-t_0) - z(t-t_0+t)}{\Delta t}$$

$$\frac{dm_i}{dt} = -\frac{A_c L_p \rho_i}{N_f} (P_i + \Pi)$$

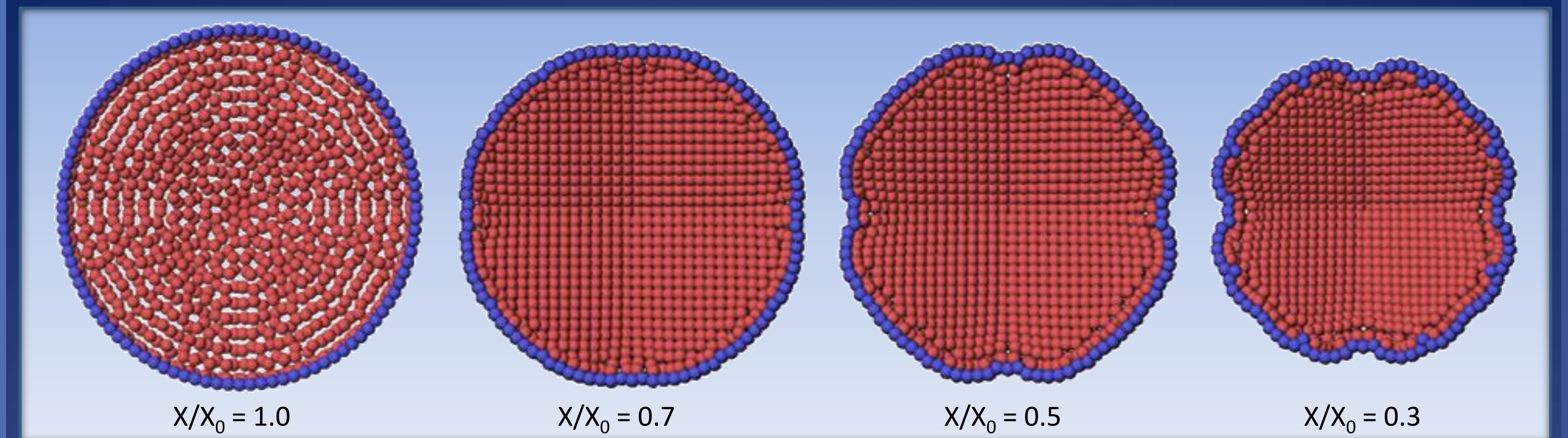
$$W_{ij} = \frac{15}{7\pi h^2} \begin{cases} \left(\frac{2}{3} - \frac{9}{8} R^2 + \frac{19}{24} R^3 - \frac{5}{32} R^4 \right) & 0 \leq R \leq 2 \\ 0 & R > 2 \end{cases}$$

$$\frac{d\rho_i}{dt} = \frac{1}{z} \frac{d\rho_i}{dt} - \frac{\rho_i^2}{z^2} \frac{dz}{dt} + \rho_i \frac{dm_i}{dt} \quad P_i = P_0 + K \left[\left(\frac{\rho_i}{\rho_0} \right)^7 - 1 \right]$$

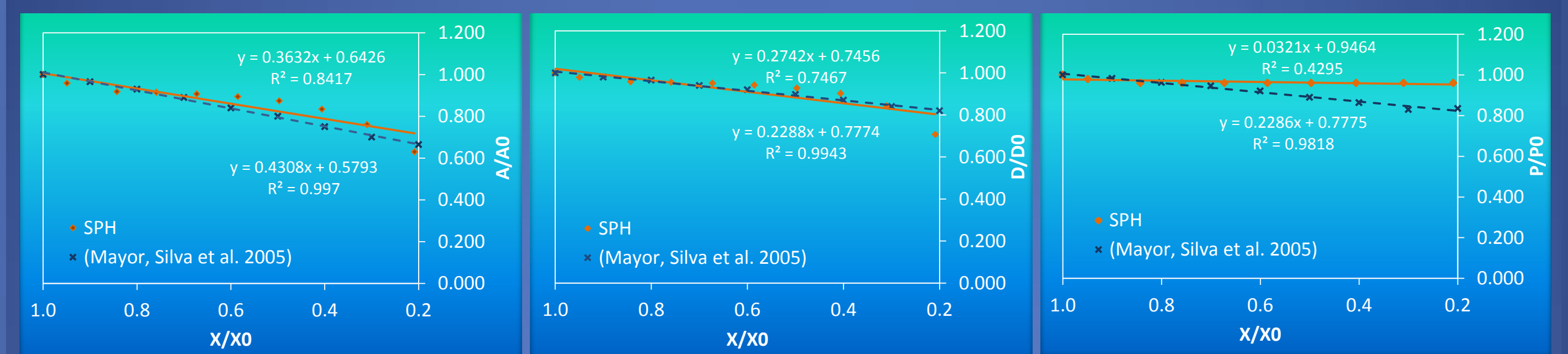
$$\frac{\rho_i^*}{\rho_i} = h \rho_i \quad R = \frac{r_{ii'}}{h}$$

Results

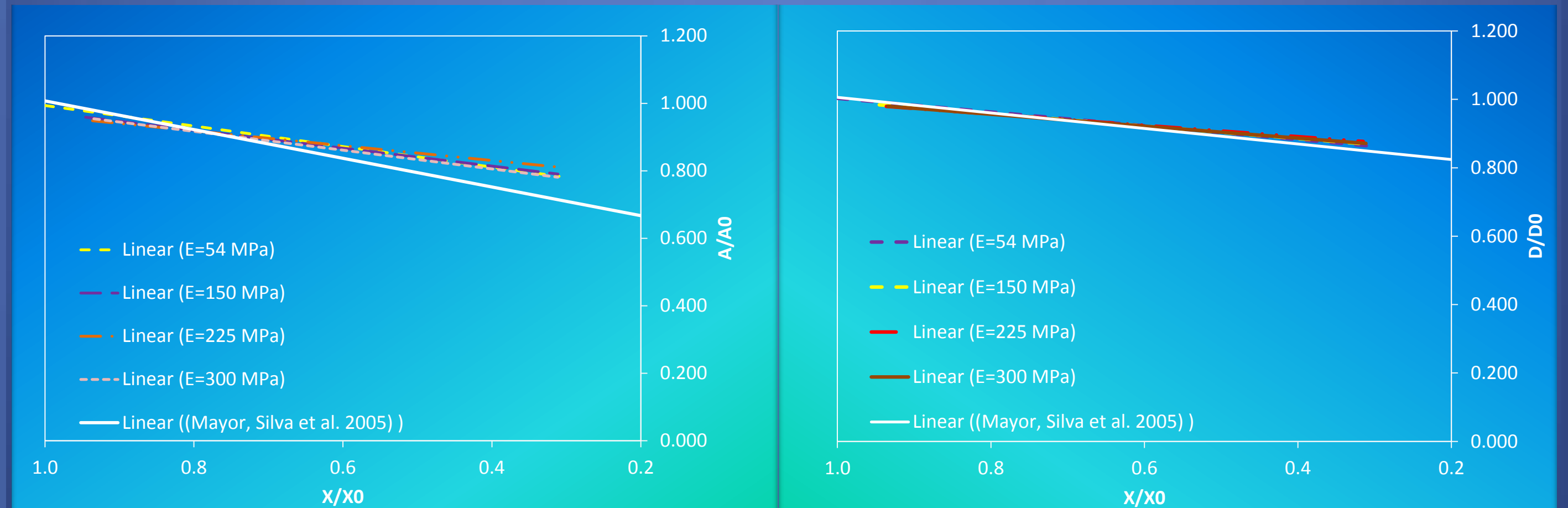
- Cellular deformations with change of moisture content (x/x_0)



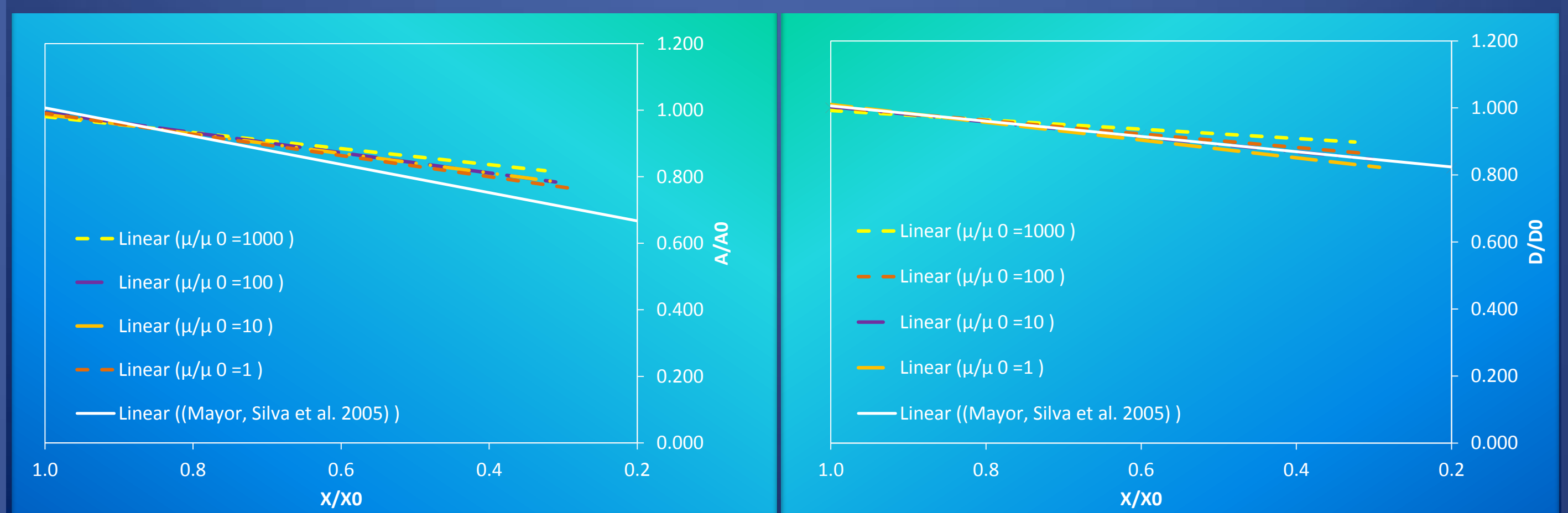
- Shrinkage predictions using normalized area (A/A_0), diameter (D/D_0) and perimeter (P/P_0)



- Model sensitivity to cell wall Young's modulus (E)



- Model sensitivity to cell fluid viscosity (μ)



Conclusion

- SPH-DEM approach:** can promisingly be used to model cellular structural changes of food materials during drying conditions
- Shrinkage Predictions (Area & Diameter):** good agreement with experiments
- Shrinkage Predictions (Perimeter):** only shows some shrinkage at the first stage of drying until some positive turgor pressure exists
- Cell wall Young's modulus:** influence on shrinkage is not so significant
- Cell fluid Viscosity:** influence on shrinkage is significant; higher the viscosity higher the shrinkage; higher viscosity values provide better match with experimental findings

Outlook

- 2-D tissue model to study effects of intercellular space and middle lamella
- 3-D single cell model
- 3-D tissue model

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